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CAUSES OF DEFECTS AND DAMAGE TO BRICK MASONRY ELEMENTS IN HISTORIC BUILDINGS

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A b s t r a c t

Ceramic brick masonry elements constitute the largest number of structural systems of historic buildings, especially sacral and public utility buildings. In the past, they were also very commonly used as a material for the construction of military facilities.

Historic buildings and masonry structures undergo destructive processes over time, the course of which can be very diverse and depends, among other things, on the physicochemical properties of the materials, the type of structure, the age of the building, working conditions and random conditions and events.

The paper is an engineering review of the causes of damage to masonry structures and indicates the need for cooperation between representatives of various specialties of science and technology, in particular architectural historians, specialists in the field of conservation of monuments, structural engineers and specialists in the field of geotechnics, geology, hydrogeologists and meliorators in order to ensure the protection of masonry structures in historic buildings.

Keywords: masonry structures, brick, damage, mortar, monuments, reinforcement, defects, revitalization

1. INTRODUCTION

Masonry elements made of ceramic bricks make up the largest number of structural systems of historic buildings, especially sacred and public buildings. In the past period, they were also very commonly used as a material for the construction of military buildings, today decommissioned and being monuments.

The following is an analysis of the impact of factors determining defects and damage to brick masonry elements in objects that can be classified as immovable monuments.

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2. CAUSES AND EFFECTS OF THE DEGRADATION PROCESS OF CONCRETE INDUSTRIAL FLOORS

Masonry buildings and structures undergo destructive processes over time, the course of which can vary greatly and depends on, among other things:

- physical and chemical properties of materials,
- type of construction,
- age of the buildings,
- working conditions,
- random events.

Some of the destructive processes are very slow, causing barely discernible changes or deformations in structural elements and brick materials [1], [2], [3]. Such, among others, include deformations that occur due to gravitational (natural) settlement. In this case, slight sagging of ceilings, settlement of supports, deformation of vaults, etc. occur after a long time. These deformations are not dangerous in technically correct buildings, if not accompanied by other negative factors. However, you should be aware that such a situation occurs in practice very rarely, and usually scratches and cracks visible in the area of brick masonry structures require the initiation of repair work, and certainly qualify the structural elements in which they occur to be observed in time to prevent the occurrence of a state of imminent danger to property, health and often life.

The aging phenomenon in brick materials and masonry structures develops under the influence of long-term exposure to the surrounding environment without the course of specific chemical reactions caused by external factors [4]. Aging is mainly influenced by physical factors occurring primarily in unshielded structures due to the action of climatic phenomena [5], and therefore repeated periodically:

- changes in the relative humidity of the surrounding air,
- temperature changes,
- direct sunlight, wind and precipitation in the form of rain and snow.

The aging process of brick masonry buildings thus follows a natural course and is difficult to stop.

The phenomenon of aging in practice is also difficult to distinguish and separate from the process of chemical decomposition. Materials and structures also gradually undergo chemical transformations after a certain period of time under the influence of harmful substances.

This phenomenon arises as a result of a series of layered and interacting physical, chemical and sometimes biological processes, with the synergistic action of these factors involving the transformation of the material through chemical reactions. A large impact on chemical destruction is exerted by the aggression of the environment surrounding masonry materials and structures.

Much of the damage to buildings and masonry structures is caused by mechanical factors, especially those caused by [6]:

- occurring transformations and deformation of the substrate on which the object is founded,
- change in water relations in the vicinity of the facility,
- shocks and vibrations usually coming from the external environment.

Harmful effects of:

- physical agents,
- chemical agents,
- mechanical agents

can accelerate:
- negative characteristics (understood as defects) of the masonry materials themselves,
- structural defects in completed masonry structures,
- conditions of use, especially conscious or unconscious human activity,
- accidental factors: fires, floods, seismic movements as well as warfare.

In analyzing the symptoms and effects of various destructive factors, the timing and impact of the immediate surroundings of the monument cannot be overlooked either.

Recording the symptoms and effects of damage, analyzing the phenomena and any circumstances conducive to destruction as well as recognizing the sources causing them are extremely important in engineering activities, especially those carried out in the area of immovable monuments of masonry structures. Without clarification of the causes inflicting damage to historic masonry elements, it is difficult to properly select technical measures for their effective protection.

2.1 Impact of climate and atmospheric processes

Materials and masonry structures built into historic buildings are in a great many cases sensitive to climatic changes. Fluctuations in temperature, humidity, precipitation and wind can have different effects, but contribute to progressive destruction.

Brick masonry structures exposed to strong solar heating or subjected to low temperatures experience spatial deformations, the extent of which depends on their massiveness. Accordingly, deformations on the surface of masonry are visible in the form of fine cracks and fissures [7].

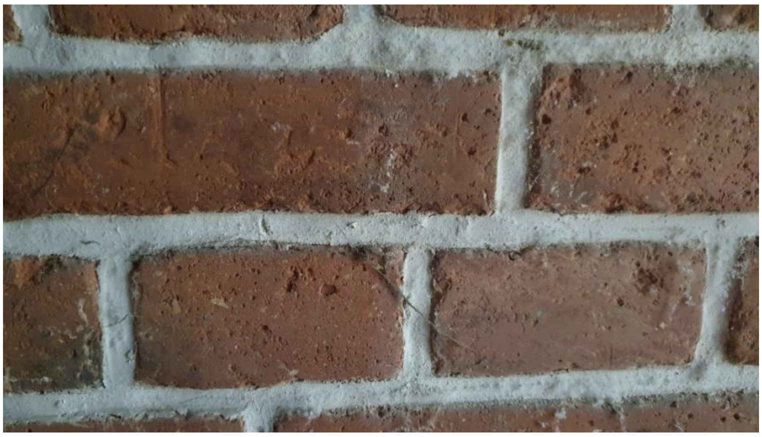


Fig. 1. Open pores and capillaries of the exterior masonry of solid ceramic brick,
visible cement mortar tight joint improperly executed in the past period during renovation work
(photo: Maciej Niedostatkiewicz)

Thermal deformations also foster premature aging of protective layers such as plaster coatings, facilitating the penetration of precipitation (rain and snow) as well as dew and fog into the brick masonry structure. As a consequence of changing climatic situations, brick masonry elements show a weakening of the homogeneity of the structure and an increase in the brittleness of the material. Brick and mortar become more porous, begin to swell or crumble, reveal a loss of substance and, as a result, their specific gravity decreases and their mechanical properties decline. This action, in turn, causes internal stresses, which, with the simultaneous action of unevenly distributed external forces (external load), leads to local stress concentration, deformation, decrease in strength and failure of masonry. However, it should be borne in mind that the extent of damage caused by this cause depends largely on the massiveness of the brick masonry element [8].

The destruction and deformation proceeds the faster the brick masonry elements' greater structural irregularities are (Fig. 1), the weaker the adhesion of mortar and the more voids, caverns, fissures and cracks there are in the masonry section.

In many cases, serious damage or destruction can be caused by winds. Direct wind action on brick masonry elements contributes to deflation and aeolian corrosion. This phenomenon is quite common in many historic buildings. It is formed by the action of the wind even at normal gust force: the wind sucks up and tears off fine and poorly bonded weathered particles from the surface of the brick, then carries them and slams them forcefully against the face planes of the materials. Such action causes rounding of sharp edges, deformation of profiles, even the formation of cramps, furrows and cracks.

The wind carries harmful gaseous substances found in the air or dissolved in rainwater or melting snow: it deposits them on the surface of ceramic masonry, as well as ceramic reliefs that are architectural decorations. In addition, with the wind, these substances penetrate into the interior of historic buildings, destroying frescoes, paintings, elements of plastic decoration and movable equipment.

The action of atmospheric processes under normal conditions and surroundings is slow and in principle does not cause great damage to brick masonry elements. This is evidenced by historic buildings that have survived to the present day for many hundreds of years [9].

2.2 Influence of topographic conditions and subsoil properties

Among the most dangerous in consequences, and at the same time the most difficult to control causes that prompt the destruction of historic buildings are those that arise in connection with the transformations occurring in the natural environment with which the object is permanently associated, and especially in the case of violation of the stability of the terrain and the subsoil.

Based on the analysis of previous cases and causes of defects and damage to brick masonry elements in historic buildings in connection with the condition of the subsoil, it can be noted that violations of the operational suitability of the ground are mainly due to the following phenomena [10], [11], [12]:

Cause A: anomalous ground characteristics

They cause periodic movements of the subsoil. Cohesive soils (silt, clay, loess, dust) in particular are characterized by these features. In this case in particular, these phenomena are strongly influenced by changes in moisture content and climatic fluctuations.

Excessive wetting of the soil occurs most often in connection with damming up of watercourses with sudden or prolonged precipitation, as well as with leaks in sewage and water supply networks. In such cases, under the foundations, the so-called collapse settlement occurs, entailing uneven settlement of individual parts of the building or collapse of the foundations, and consequently the formation of cracks and fractures in the walls and other structural elements of the building, including the historic building.

Cause B: improper structural solutions for foundations

In this case, stresses in the ground are particularly adversely affected by:

- objects with an elongated in one direction or refracted outline,
- objects having technically incorrect shape of foundations,
- objects having an arrangement of solids that is not statically balanced, characterized by a large disproportion of the impact on the subsoil.

Cause C: improper land use in the facility area
Following such a situation, the natural properties of the land are violated and unfavorable conditions are created for the facility and its surroundings, as a consequence of, among other things:
- land leveling, including the construction of embankments,
- destruction of greenery and forests,
- improper above- and below-ground operations of the subsoil.

The problem of improper exploitation of the underground part of the subsoil is particularly relevant to areas lying within the range of old and new underground workings. In these cases, as a result of tectonic movements over the collapsing pit, a subsidence basin is formed, causing a change in the configuration of the terrain: concavities are formed, elevations, soil creep occurs, entailing a violation of the equilibrium of the earth's ground masses and, as a result, serious damage to objects, resulting in pre-failure conditions, failures and even building disasters [13].

As far as historic buildings are concerned, it is also often the case that cracking and displacement of individual parts of them, including masonry also occur in the area of old urban districts due to the collapse of formerly existing underground structures, such as multi-level underground parts, passages and canals.

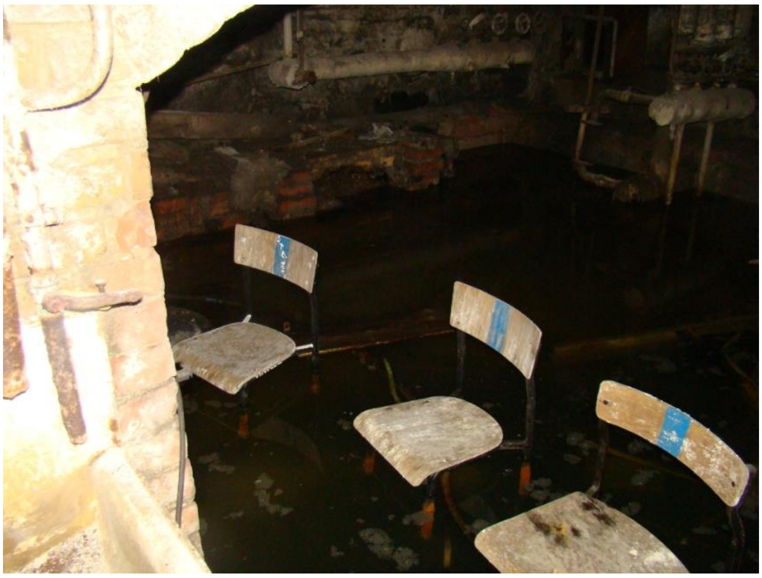


Fig. 2. Flooded basement of the building to a height of 0.45 cm above the level of the basement floor: the original groundwater level ~120 cm below the foundation level of brick footings (difference between the original state and the state shown in the illustration: ~265 cm) (photo: Maciej Niedostatkiewicz)

Cause D: changes in hydrogeological conditions
These phenomena occur as a result of transformations in nature, conscious or unconscious human activity, or other causes that cannot be predicted in advance.
Particularly dangerous phenomena that have a destructive effect on the subsoil include:
- lowering of the groundwater table,
- changing the direction of flow and groundwater levels (Fig. 2).

In both of the above-mentioned cases, these phenomena occur most often as a result of changes in water relations in the vicinity of the monument, as a consequence of, among other things:
- regulation of rivers and streams,
- destruction of the drainage system,
- technically inappropriate lowering of the groundwater table.

A change in water relations or moisture content has a very adverse effect on the strength properties of the subsoil under the foundations. This applies in particular to foundations made as brick walls sunk into the ground, regardless of whether they were made as walls with offsets (banquettes) or realized with the wall thickness preserved as in the above-ground part. In many soils, due to the flow of water or its oscillation, fine and dusty fractions are washed out. These processes entail changes in the structure of the soil and subsequent loss of initial durability.

A similar phenomenon occurs in soils that are moist or saturated with high standing groundwater during freezing. Under the influence of freezing and, in turn, thawing, significant deformations are created in the ground, which is very detrimental to the foundations and underground parts of the structure of the building. It should be noted at this point that brick masonry structures are very sensitive to the phenomenon described above.

The slow but gradual disruption of the earth masses' equilibrium can also be caused by the favoring geological structure of the terrain and periodic increases in precipitation [14]. In irrigated areas, groundwater is disturbed, the equilibrium of the terrain is disturbed, the terrain is cracked and landslide movements are formed as a result.

The above-described causes are particularly dangerous for brick masonry elements which, in most cases, are structural elements of historic buildings and show high sensitivity to subsoil deformation.

2.3 Effect of water and moisture

Water in all its forms, i.e. in the form of steam, liquid and ice, is undisputedly the factor causing the greatest destruction in most structural and finishing elements, including brick elements. Moisture, penetrating into the structure of brick masonry, causes mechanisms that generate harmful changes, following the course of physical, chemical or biological processes occurring most often in interconnection. This situation occurs very often in the case of brick masonry structures that are structural elements of historic buildings [7], [15], [16].

In brick masonry structures, the appearance of moisture can be caused by:
- absorption of moisture contained in the air by porous and hygroscopic materials and mortars,
- penetration of water vapor into pores and cracks and condensation inside the structure or on its surface,
- surface wetting during precipitation or infiltration and seepage of water from other sources into the walls,
- capillary rise of water from the ground.

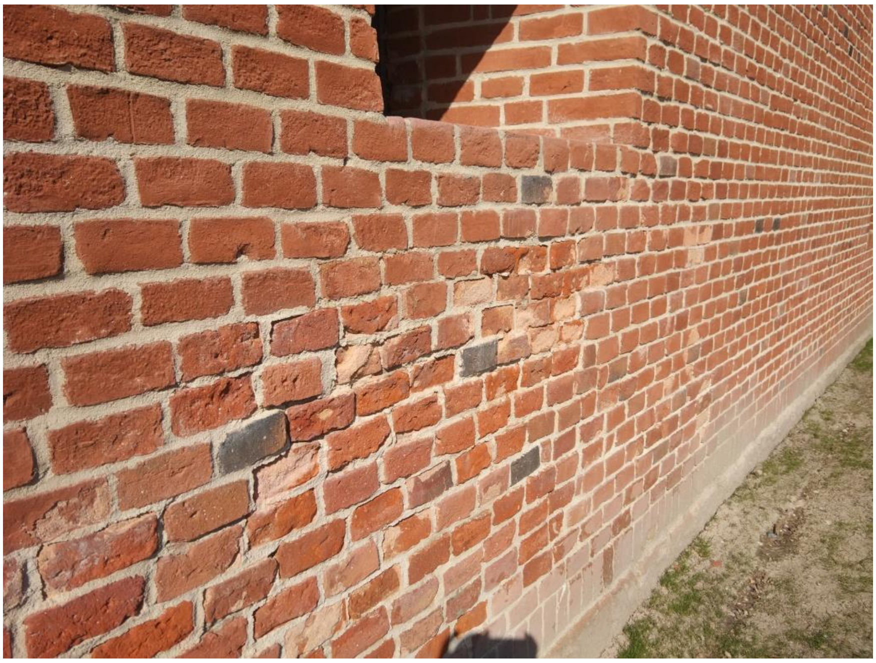


Fig. 3. Frost damage to the exterior masonry of solid ceramic brick,
visible damage caused by the erosive action of wind
(photo: Jacek Zabrocki)

Dampness of the masonry structure, especially brick masonry in historic buildings is the first stage in the process of their deterioration, especially when the water contains harmful or aggressive admixtures.

Ceramic masonry, carrying dead weight, load resulting from the structural, environmental and technological system, characterized by a heterogeneous structure, having hygroscopic materials in its composition, during the process of water saturation become less resistant to deformation, losing their initial load-bearing capacity, first of all, compressive strength [17].

Water seeping into masonry causes brick masonry materials and mortars to swell and gradually dissolves the bonding agents. Seeping through the masonry, the water contributes to the mechanical leaching of the mineral components of mortars and the weaker bonded grains of materials, which promotes the intensity of the deflation, ablation and corrosion phenomena (Fig. 3).

During the period of reduced temperatures, during freezing, water turning into ice increases its volume by ~9%, thus causing a significant increase in pressure on the surrounding material. Already when the temperature drops to 0^0C, the pressure on the wall of the material is ~100 kG/cm^2 (10 MPa), at -10^0C the pressure increases to ~1139 kG/cm^2 (113.9 MPa), and at -20^0C the pressure increases to ~2050 kG/cm^2 (205.0 MPa). As a result of this phenomenon, excessive deformations are generated in the material, which, in the weaker parts of the cross-section of the structure, cause violation of the cohesiveness and compactness of the structure, displacement or cracking of the brick. Periodic changes in melting and freezing facilitate erosion, and the penetration of other corrosive agents can quickly lead to an immediate threat to the safety of the structure, ultimately resulting in the initiation of a building disaster [16].

Parts of masonry structures sunk into the ground and in contact with it they are subject to moisture due to the fact that the soil in practice is always saturated with more or less water. The ability of capillary rise of water in masonry, above the level of water-saturated ground depends on the structure of the brick masonry, but it is assumed that it can reach up to ~3 m. If, in such a case, the ground water contains harmful components for brick masonry, such as organic acids, dissolved salts or lyes, then the brick elements and mortars that are not resistant to their chemical reactions undergo unfavorable transformations, and ultimately disintegrate.

Water flowing in streams or rivers, or water flowing down the surface of the land towards it, seeping into the ground and contributing to the violation of the hydrogeological system of a particular substrate, can also be dangerous to a historic monument building.

During floods, water pushes against the lower parts of structures, dilutes the ground and exposes foundations. Often the surging and piled-up waters wash up the banks and cause the sliding and creeping of the earth masses on which the structures, especially immovable monuments, stand.

In many cases, the reason for the destruction of brick masonry structures is the action of corroding steel elements. Moisture accelerates the corrosion of, for example, steel anchors, by means of which walls are tied in horizontal planes to ceilings. As a result of corrosion, anchors or other elements fixed in the masonry, such as hooks, brackets or hinges, increase their volume significantly and become the cause of bursting of the masonry structure, especially brick masonry.

Moisture can also cause a destructive effect on the durability of ceilings on wooden beams, and through them, indirectly on masonry. Wooden beams that are not protected from the effects of moisture, especially at the supports, are subject to deterioration due to the development of biological processes, as a result of which, due to the weakening of the ceiling cross-section, the vertical partitions on which they are supported may be fractured. Similar effects can also be caused by corrosion of floor steel beams.

With the far-reaching destruction of the cross-section of floor beams and anchors, the cooperation of horizontal bracing structural elements with vertical partitions, such as exterior and interior walls, is compromised. As a result, floor deformations increase, accompanied by increased reactions transferred to the walls. Walls not restrained by beams or anchors undergo excessive displacement or buckling, which inevitably leads to the occurrence of pre-failure conditions, failures and, in extreme cases, to a building disaster.

Rapid and uncontrolled drying may also prove dangerous in brick masonry that is highly moist. During drying of brick materials a gradual dehydration of mineral substances occurs, resulting in the phenomenon of shrinkage of individual components of the brickwork; shrinkage, in turn, causes the formation of surface stresses, consequently fracturing, development of cracks, gradual delamination, falling off and flaking of the surface layers and later also in the deep parts of the brickwork.

It should be noted that the destructive effect of water and moisture is the more intense, the more dissolved substances penetrate into the masonry, destroying brick elements and mortar.

2.4 Impact of aggression of the surrounding environment

Historic buildings, located in large cities or near highly developed industrial centers or in the immediate vicinity of the maritime climate, are exposed to slow corrosion processes due to aggressive substances in the atmosphere and water.

In the atmosphere, harmful substances are formed from dust, fumes, gases and vapors. Harmful substances from chimneys carried by the wind attack masonry surfaces.

Aggressive chemical compounds in surface water can come from atmospheric water, which dissolves a number of gases in the air, from industrial and municipal wastewater, from soot particles settled on the ground surface permeate and dust, which come along with rainwater or melting snow of the ground, and from components contained in the soil and groundwater or other sources [18], [19].

For historic buildings of brick masonry, a particularly great danger arises when their structures are unprotected, and the given environment is rich in moisture and aggressive sulfate, carbonate, chlorine, and phenolic compounds. Aggressive volatile and liquid substances settle on the external surfaces of the structures, as well as penetrate into the interior of the structure and, by chemically combining with certain components in the materials, cause their destruction.

The effectiveness of the results of environmental aggression depends mainly on the nature and concentration of the substances, the conditions of action and the resistance of the brick masonry itself. The effect of the substance causing destruction can occur by means of their chemical reactions with the brick masonry in an aqueous environment, oxidation, carbonization and hydration.

Destructive processes in masonry are particularly vigorous in a hydrated environment if it abounds in dissolved acids, especially sulfuric acid (H_2SO_4), carbonic acid (H_2CO_3), nitric acid (HNO_3), lyes, alkalis of appropriate concentration, and all kinds of dissolved sulfate salts, especially sodium sulfate (Na_2SO_4), magnesium sulfate ($MgSO_4$) and ammonium sulfate (NH_4SO_4).

Brick masonry deterioration processes are also very dynamic in humid air environments, especially with active gases such as chlorine (Cl_2), hydrochloric acid (HCI), hydrogen sulfide acid (H_2S) and hydrogen fluoride (HF). Fluorine itself (F) and hydrogen fluoride gas (HF) are particularly toxic.

Corrosion processes are slowest in air-dry environments, as well as when the ambient air temperature drops below 0^0C. At very low temperatures (below -25^0C), corrosion processes in practice cease. Nevertheless, even under such conditions, airborne gases such as carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), sulfur trioxide (SO_3), carbon disulfide (CS_2), as well as hygroscopic salt dusts of which potassium chloride (KCI), sodium chloride (NaCl) or other harmful substances are examples, attack and destroy masonry construction materials, including brick elements.

It should be noted that the negative effects of harmful compounds on brick materials and masonry structures are not immediately noticeable, especially when the air or water is contaminated to a small extent, or when the process of destruction proceeds without a clear loss of mass.

The first sign of chemical changes in brick masonry materials is visible on the surface of the brick by means of occurring whitish-gray spots, various types of tarnish, efflorescence, infiltrations, swellings and flaking of the outer layers. From here, corrosion gradually penetrates deep into the material, causing the crumbling of the mass of the component parts of the structure and their disintegration. Aqueous solutions of compounds that react with dissolved mineral components to form salts are particularly dangerous for brick masonry materials. With increased moisture in masonry, salts dissolved in water form crystals in pores, capillaries and leaks. The pressure caused by the crystallizing salts is many times greater than the pressure of freezing water and causes the structure of the materials to burst.

Surface and cavity corrosion processes in mineral materials primarily develop in elements and materials that are less resistant, partially contaminated with sand, oxides of iron contained in silicates, carbonate or organic substances, as well as in structures located in the most favorable conditions for corrosion. The nature of damage to brick masonry elements due to aggressive substances is most often very diverse and frequently complex. These elements in historic buildings are particularly vulnerable to corrosion, especially when they have an overloaded and hygroscopic structure [20].

2.5 Impact of biological processes

Factors that can cause significant damage to the area of brick masonry elements in historic buildings are those of a biological nature [21].

Biological processes occur quite commonly as a result of fungi, insects, plants, bacteria, and often animals and birds. The destructive effects of these organisms on brick masonry elements can occur directly or indirectly through other structural elements.

Fungi, mold, insects and bacteria usually attack organic elements that may dwell in the masonry structure or with which the masonry is directly connected, such as wooden ceiling beams or elements of the wooden roof trusses.

The spread of the so-called house fungus is extremely extensive. Under favorable conditions, pine wood infested by the fungus loses more than 90% of its initial endurance, primarily in terms of compressive strength, within a few months, which can lead to the destruction of structural elements of the building, including the uncontrolled sinking or collapse of brick masonry elements.

Active bacterial and fungal activity can be recognized not only by the appearance of mold and plaques on structural parts, but also by the characteristic odor.

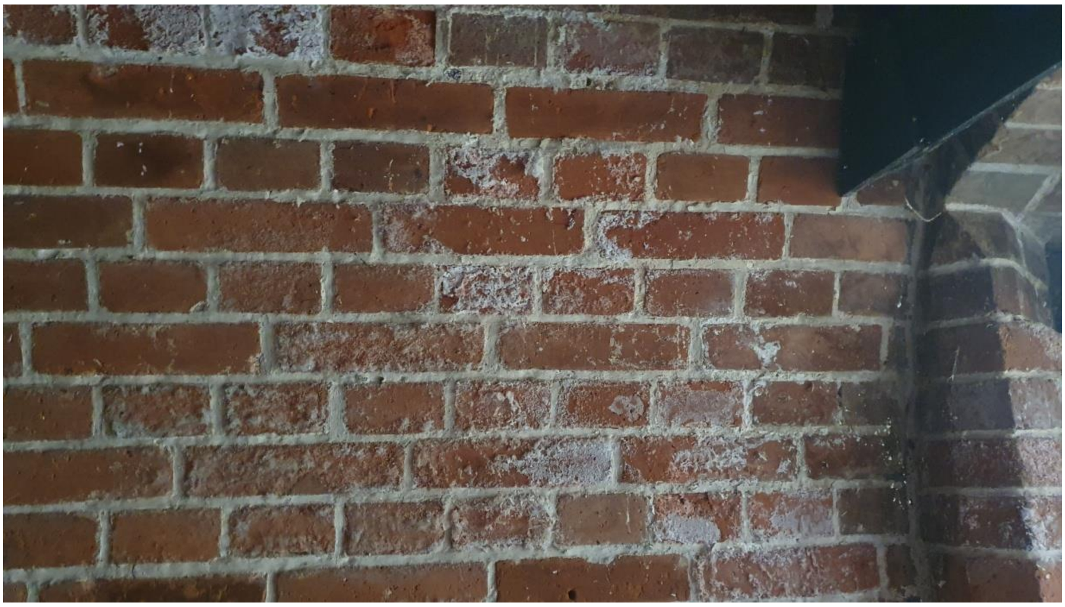


Fig. 4. Development of biological corrosion on the interior surface of the exterior solid ceramic brick masonry, visible cement mortar tight joint improperly executed in the past period during renovation work (photo: Maciej Niedostatkiewicz)

Intense fungal growth can become a reason for the rapid decomposition of mortars used in the erection of masonry structures, since a number of microorganisms under favorable physicochemical conditions such as elevated temperature, increased humidity, acidic environment, develop on inorganic substrates (Fig. 4). These microorganisms cause corrosion and decomposition of limestone, dolomite, marble, granite and other mineral materials containing silicates and aluminosilicates, which are very often admixtures to mortars. Biological corrosion most severely destroys mortars containing calcium compounds.

The effect of plants, especially grass, trees, creepers and mosses, which entwine or grow on the surfaces of unprotected brick walls, can also prove very harmful. Roots, penetrating deep into joints and cracks, by the force of expansion burst and crumble small-size elements (bricks) and loosen the joints. Following this action, conditions are created that favor the penetration of other destructive factors, especially moisture.

The harmful effects of insects, commonly known as technical wood pests, on wooden structures are well known. It should be noted that with prolonged action of insects, not only the weakening of load-bearing structures can occur, but also damage to masonry systems due to the adverse effects of deformed wooden elements. This situation applies primarily to immovable monuments in which renovation and repair work is not carried out, or is carried out slowly or even improperly.

The destructive effect on brick masonry elements of domestic animals, especially cows and horses, and birds, especially pigeons, should also be mentioned here. Animals contribute, among other damages, to the growth of moisture and the secretion of harmful salts that result in the development of destruction of masonry elements.

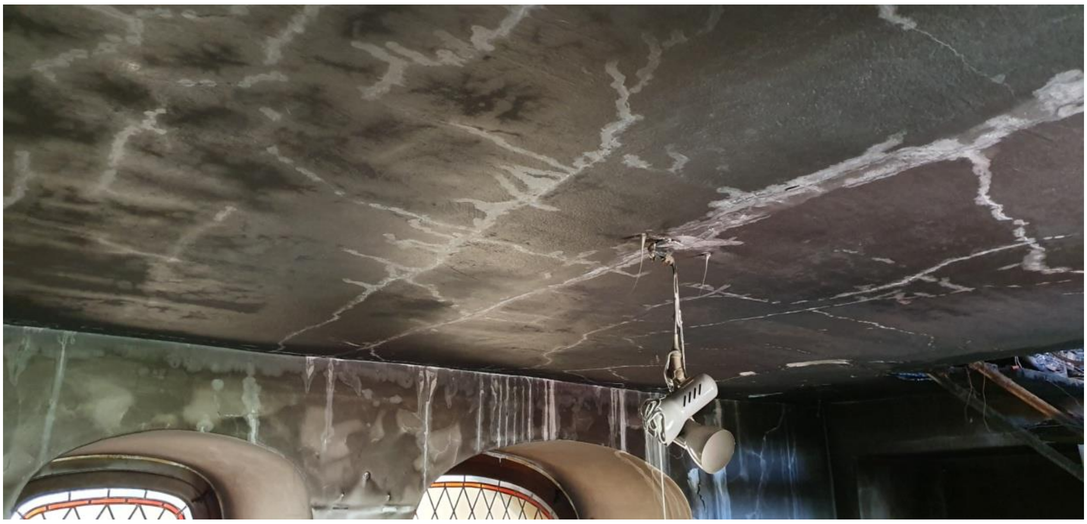


Fig. 5. Fire damage to solid ceramic brick wall and ceiling on wooden beams, visible cracks in plaster on wall and ceiling (photo: Maciej Niedostatkiewicz)

Birds are a common cause of various types of damage to masonry elements of an aesthetic nature, with pigeon manure (droppings) containing phosphoric acid likely to be particularly destructive to brick elements.

2.6 Impact of high temperatures

Temperatures resulting from a fire [22], even of short duration, have a destructive effect on both the brick masonry elements and the mortars that were used to erect them. As a result of the action of fire, which, as a rule, can be described as an exceptional (incidental) load, additional inter-particle stresses and deformations develop in the structure of masonry elements due to their uneven expansion and change in volume, the so-called temperature stresses. This phenomenon is the cause of the formation of cracks on the surface of brick masonry, the separation of individual layers of bricks, flaking and crumbling, and the subsequent loss and weakening of the masonry section (Fig. 5). With prolonged heating in the mass of brick masonry materials, further changes of a physical and chemical nature occur, most notably dehydration of binders, an increase in porosity and a decrease in the mechanical strength of the masonry as a whole. Previous experience based on laboratory tests shows that already at a temperature of 200^0C the compressive strength of brick masonry materials decreases from ~10% to ~33%, and at a temperature of 500^0C this decrease is even more significant and reaches an average of ~50%. In the aftermath of a fire, in most cases, irreversible displacements and deformations occur in the structural system of a building, especially when in the case of a historic building it is a brick masonry structure, which in turn become particularly dangerous when the structural system is under heavy loads, resulting both from the weight of the structure itself and those resulting from environmental loads.

High temperatures can be caused not only by fires, but also by lightning strikes, as well as explosions of explosives with which we are confronted during emergencies and armed conflicts. In these cases, the destruction of building structures is further increased by the accompanying shocks and to a large extent the use of water used during rescue operations.

The described situations cause very extensive destruction and damage to brick masonry elements in objects that are immovable monuments.

2.7 Impact of shocks and vibrations

In many cases, the cause of cracks and cracks in historic buildings is shocks and vibrations, which can result from the movement of people or machinery inside the building, or vibrations transmitted to the building from external sources [23]. This can be the movement of heavy motor vehicles passing nearby, explosions in the operation of open-pit mines or quarries, the collapse of mine workings, underground chambers, caves and caverns, as well as vibrations caused by the flight of aircraft, the ringing of bells. A separate group as a source of destructive shocks and vibrations comprises vibrations of the ground and air, generating in practice unpredictable damage to historic buildings, including military activities carried out during emergencies and armed conflicts.

As a general rule, historic buildings located in cities or in heavy-traffic districts of metropolitan areas are particularly exposed to shocks and vibrations [24]. Heavy motor vehicles moving on the roadway, as well as rail vehicles moving on tracks, cause vibrations of the surface. These vibrations transmit through the subsoil to historic buildings and become the cause of their damage, similar to seismic vibrations.

Seismic phenomena, even of insignificant force, cause cracks in masonry, especially heavy and massive masonry structures. Particularly vulnerable to seismic shocks are buildings that are already scratched and fractured, as well as those that have been subjected to reconstruction and expansion in the earlier period conducted with disregard for the principles of technical knowledge, and whose current technical condition, due to errors and shortcomings in design and execution, as well as the lack of ongoing repairs, is unsatisfactory, or even outstandingly unsatisfactory.

2.8 Impact of design and execution errors and shortcomings

Design activities and activities directly related to the implementation of these objects are also direct causes of defects and damage occurring in historic buildings.

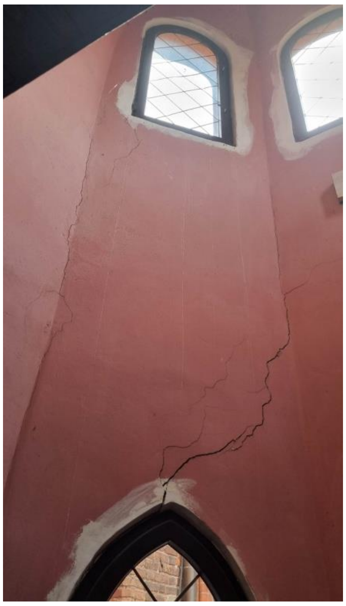


Fig. 6. Cracking of the exterior masonry of solid ceramic bricks caused by above-normal settlement of a section of the building (photo: Maciej Niedostatkiewicz)

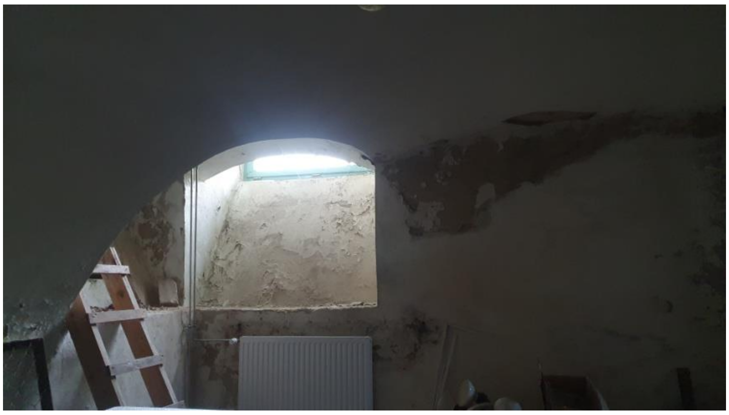


Fig. 7. Dampness of the external wall made of solid ceramic brick caused by the lack of vertical damp proofing in the part sunk in the ground (photo: Maciej Niedostatkiewicz)

In the case of historic buildings from a bygone period, especially with regard to medieval and Gothic religious buildings, it should be remembered that their implementation was based on the professional experience of the builders of the time [25], [26]. Design documentation was simplified, or reduced to a drawing (painting) which, using modern terminology, corresponded to a conceptual design. The solutions adopted and directed for implementation were not supported by detailed static-strength calculations: this also applies to the construction of brick masonry and brick vaults, commonly used in religious buildings. However, taking into account the time realities inherent in the period of implementation of this type of buildings, it can be assumed that the main design errors and shortcomings include:

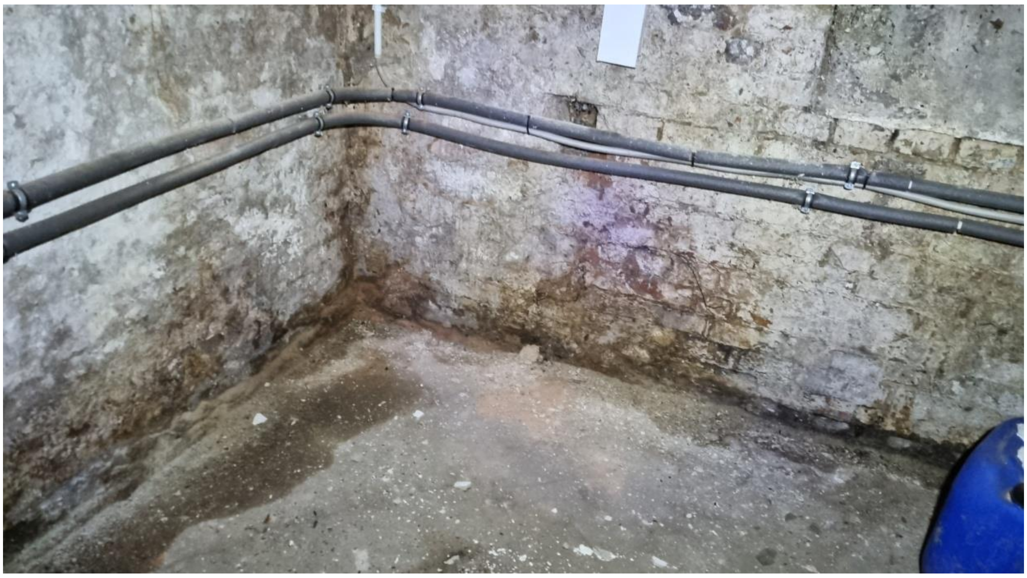


Fig. 8. Dampness of the external masonry of solid ceramic brick caused by the lack of horizontal damp proofing in the part sunk in the ground and the lack of technical efficiency (leakage) of the vertical damp proofing membrane (photo: Maciej Niedostatkiewicz)

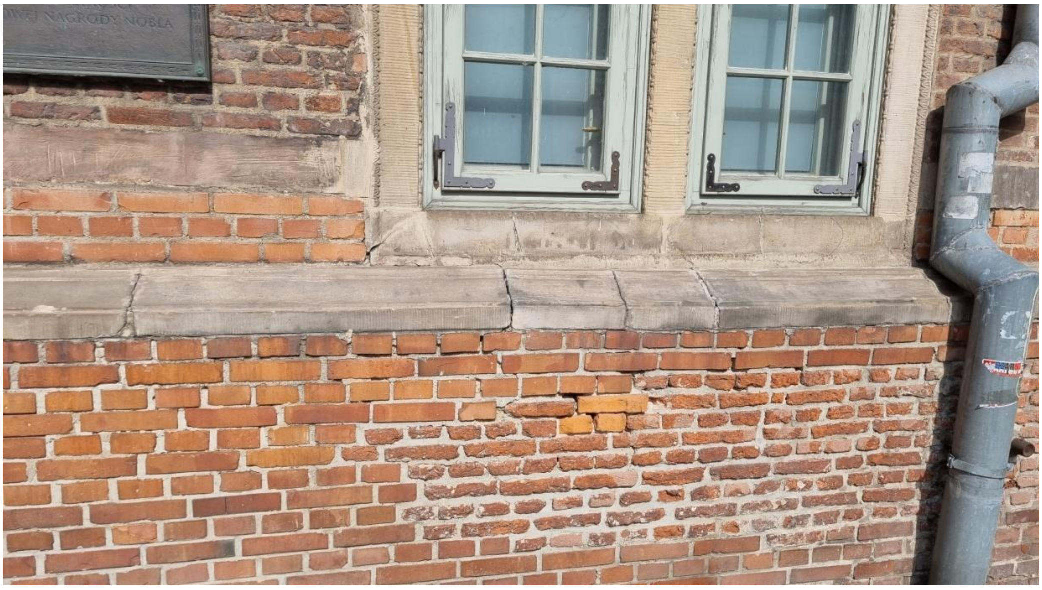
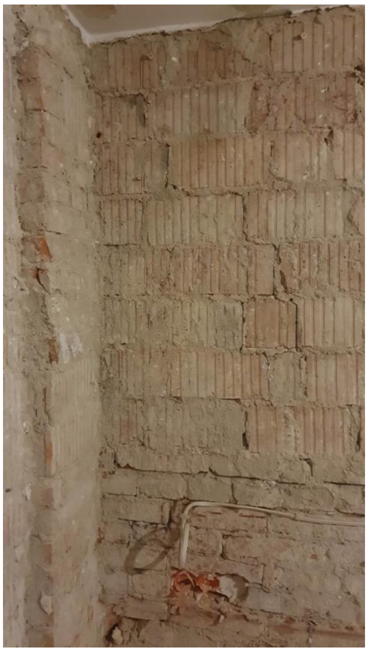


Fig. 9. *"Hollow joints"* of the exterior masonry of solid ceramic brick, additionally visible frost damage and weathering of the wall (photo: Maciej Niedostatkiewicz)

a) b)



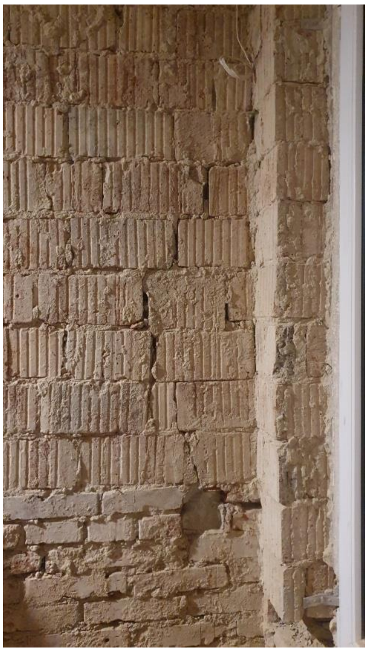


Fig. 10. Thorough cracking of the interior transverse wall made of ceramic grid brick at the point of connection with the exterior longitudinal wall made of ceramic solid bricks in a building with wooden beam ceilingsnot having frontal and lateral anchoring (photo: Maciej Niedostatkiewicz)

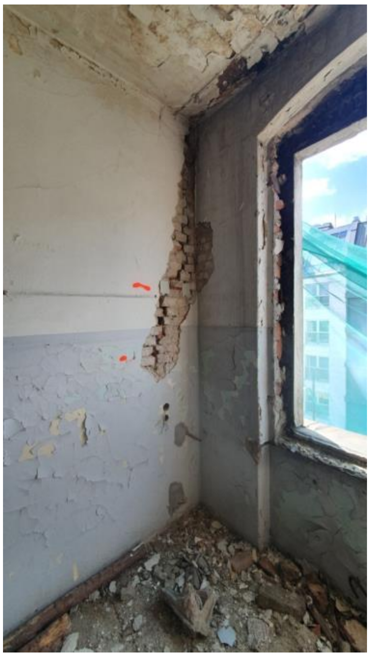


Fig. 11. Cracking of the internal transverse wall made of solid ceramic bricks at the point of connection with the external longitudinal wall in a building with ceilings on wooden beams that do not have frontal and lateral anchoring (photo: Maciej Niedostatkiewicz)

Fig. 12. Building with layered exterior walls (with air cavity),
made of ceramic bricks: a) solid, at the level of the ground floor, b) trusses, at the level of the first floor
(photo: Jan Niedostatkiewicz)

- underestimation of bearing capacity of brick footings (Fig. 6),
- the use of so-called poor masonry as a structural solution, i.e. masonry with an outer and inner layer made of fine ceramic elements and an inner filling of brick rubble,
- underestimating the load-bearing capacity of slender brick window pillars,
- underestimation of the load-bearing capacity of brick vaults, especially cross vaults.

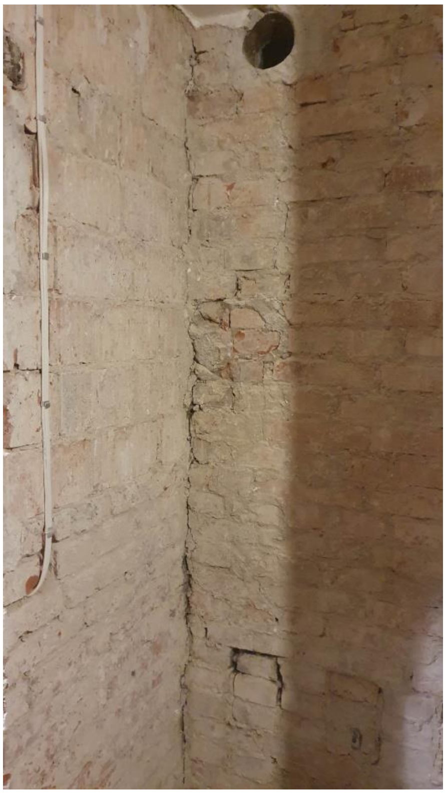


Fig. 13. No masonry bond between transverse and longitudinal interior walls
made of ceramic solid brick
(photo: Maciej Niedostatkiewicz)

In terms of execution errors and shortcomings in historic buildings dating from a bygone period with regard to brick masonry, the following problems stand out:

- lack of implementation of damp proofing or waterproofing of vertical parts of brick walls sunk into the ground (Fig. 7),
- failure to perform horizontal damp proofing (Fig. 8),
- failure to preserve the offset of transverse dividing lines in brick masonry, the so-called overlapping of transverse joints,
- failure to maintain parallelism of horizontal welds,
- implementation of brick masonry with so-called "*hollow joints*" (no joint filling for the entire width of the wall) (Fig. 9),
- perforation of masonry with longitudinal and transverse channels for the conduct of installation components,
- lack of frontal and lateral anchoring of wooden and steel floor beams embedded in brick wall sockets (Fig. 10 and Fig. 11),
- absence or incomplete filling of the armpits of brick vaults,
- implementation of the walls of individual floors from different materials, including ceramic, in order to reduce investment costs (Fig. 12),
- lack of masonry bond between individual vertical partitions made of fine ceramic elements (Fig. 13).

The aforementioned errors, shortcomings and design and execution omissions, if not corrected during the lifetime of the historic building, in most cases contribute to the successive deterioration of its technical condition over time.

2.9 Impact of operating conditions and use

A great influence on the technical condition of historic buildings is directly exerted by man. As a result of human actions, whether conscious or unconscious, the original proportions and harmony of the visual and functional-utility layout of the object are usually disturbed, and often also the logic and expediency of the basic structural system, which in the case of historic buildings is made very often as a masonry construction of small-sized ceramic elements.

Many historic buildings, in years gone by, underwent adaptations or alterations during their use, often resulting from current social or political demand. Often these changes, perhaps even expedient from a functional-utility point of view, were carried out in disregard of the principles of technical knowledge and professional art.

Based on engineering practice, it can be concluded that in the case of historic buildings, the durability of brick masonry structures has been particularly adversely affected by:

- changing vaults to beamed roofing or vice versa,
- punctures and widening of window and door openings,
- removal of load-bearing walls to expand usable space,
- demolition of the masonry casing of pillars and columns,
- removal of steel pulls,
- introducing additional vertical partitions to create more rooms.

In addition, serious damage also occurred as a result of either overloading the structure or changing the nature of the load, particularly from static to dynamic.

Damage to historic buildings also occurred as a result of overloading structural elements, for example, during the conversion of public buildings or religious buildings into warehouses.

Careless storage of various types of materials and equipment, particularly in historic buildings converted for use as either manufacturing or storage facilities, has become one of the common causes of damage to ceramic masonry elements in these facilities.

A fairly common phenomenon that causes premature loss of technical value of a historic building is failure to maintain it properly or even lack of concern for the object's durability (Fig. 14 and Fig. 15).

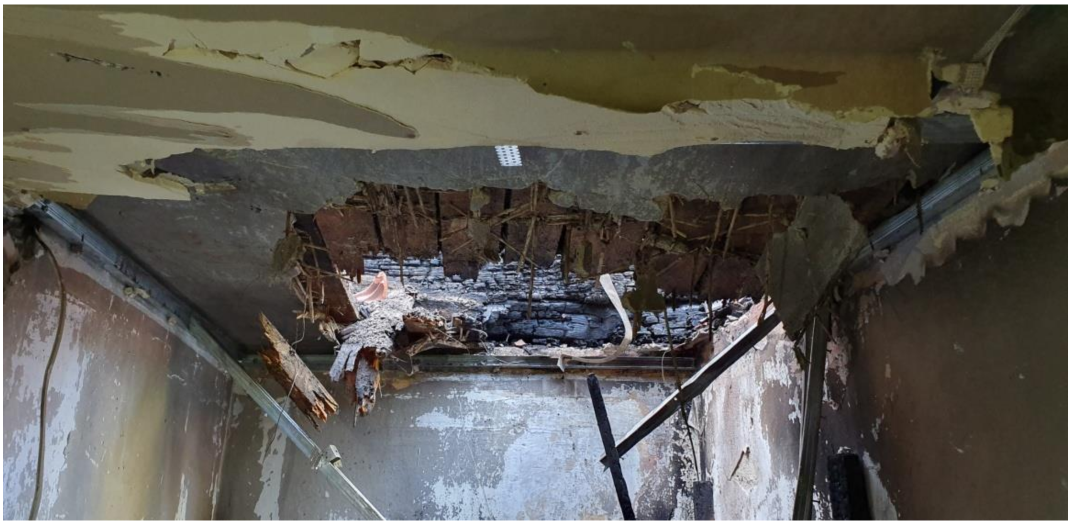


Fig. 14. Moisture damage to exterior and interior ceramic walls as a result of water flooding at the site of a broken roof (photo: Maciej Niedostatkiewicz)

One of the measures that counteract the uncontrolled and progressive decapitalization of an immovable monument is conducted in accordance with the requirements of specific regulations:

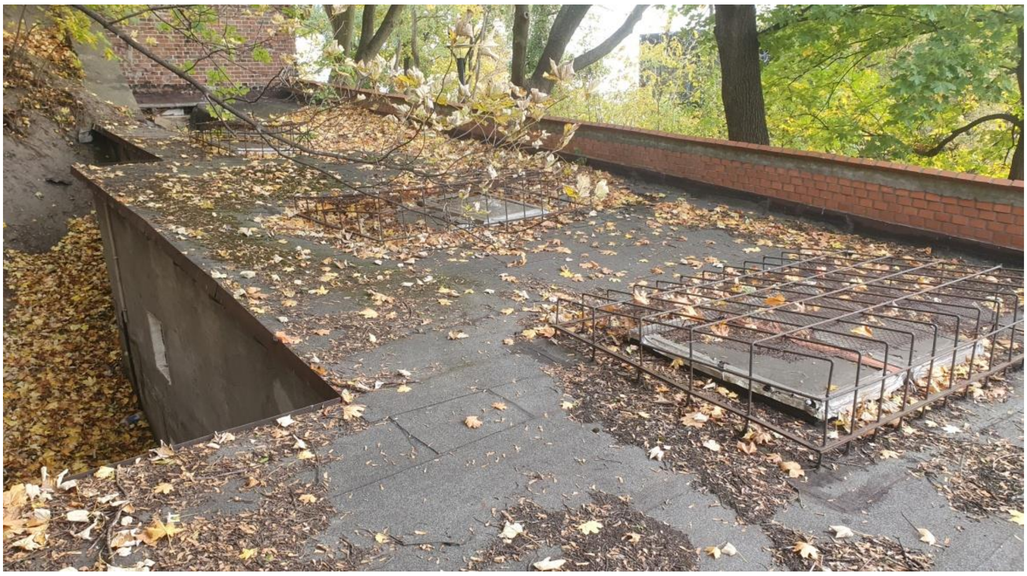
- *Inspection of technical condition (known as annual inspection),*
- *Inspection of the technical condition and suitability for use of the building, the aesthetics of the building and its surroundings (the so-called 5-year inspection).*

Their implementation makes it possible to identify the most necessary activities required to ensure the safe use of the historic building, while at the same time allowing the development of a long-term renovation plan, including planning to carry out a major overhaul of the building if its implementation is possible for conservation reasons.

In the case of objects that are immovable monuments, the plan of renovation and repair works must obtain a promise of implementation issued by the locally competent conservation authority. In the case of some objects, carrying out repair and renovation works requires the development of a detailed *Conservation Works Program.* During the development of this *Conservation Works Program,* the specifics of the structural system of the immovable monument must be taken into account, including the possible construction of its structure from small-sized ceramic elements.

The renovation documentation developed in accordance with the recommendations of *Conservation Works Program,* makes it possible to safely carry out works related to the reconstruction and expansion of immovable monuments (Fig. 16), including carrying out works aimed at the ultimate change of use of the historic building (Fig. 17 and Fig. 18).

a)



b)

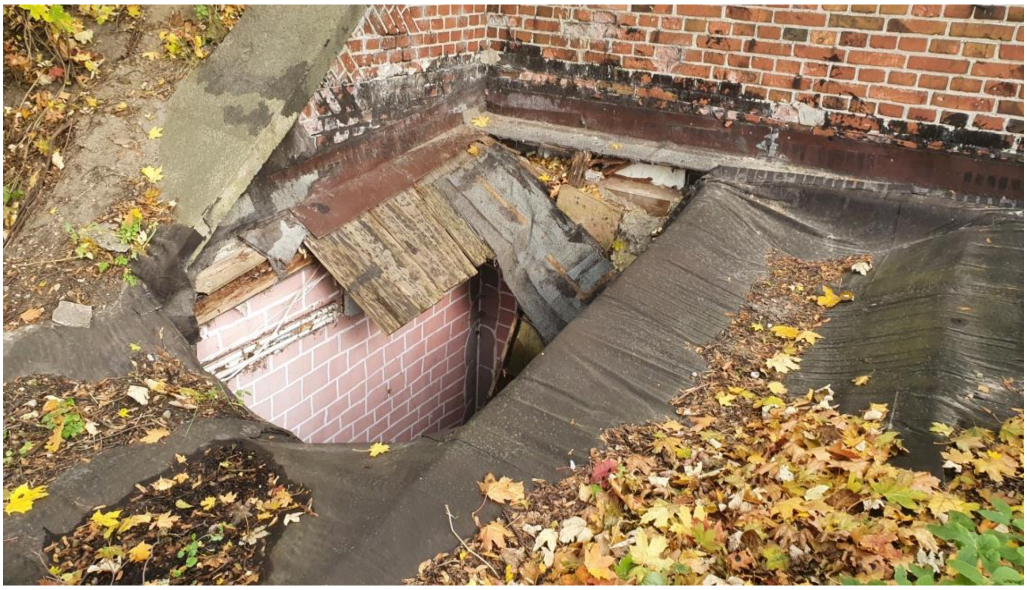
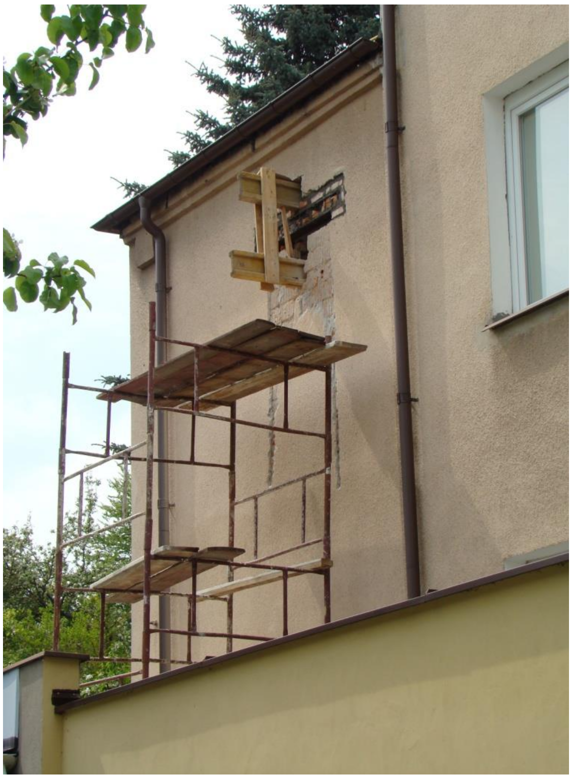


Fig. 15. Moisture damage to ceramic masonry as a result of water flooding caused by the collapse of a moisture-damaged and biologically corroded wood-framed roof: a) view, b) close-up (photo: Maciej Niedostatkiewicz)

a)



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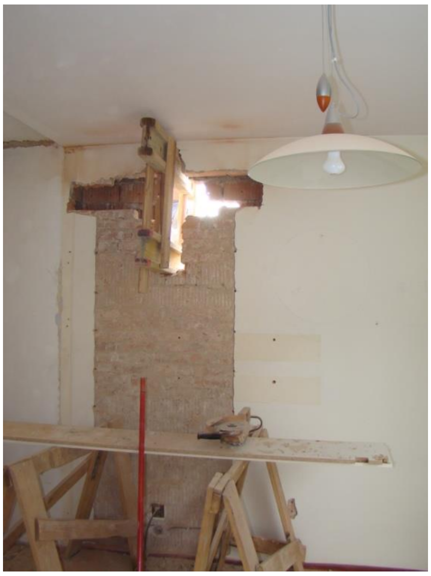


c)

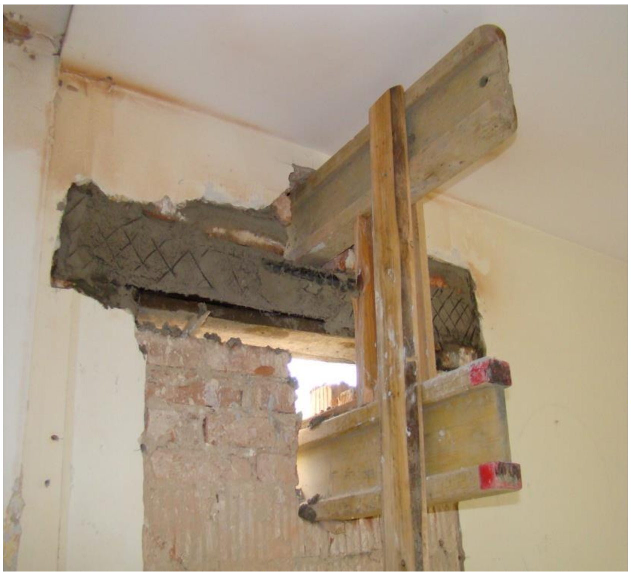
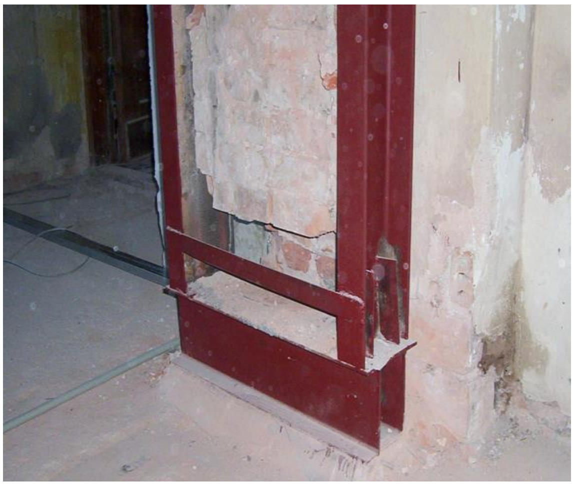


Fig. 16. Realization of the door opening in the layered external wall made of ceramic lattice bricks – stages of realization in the view from: a) exterior, b), c) interior
(photo: Maciej Niedostatkiewicz)

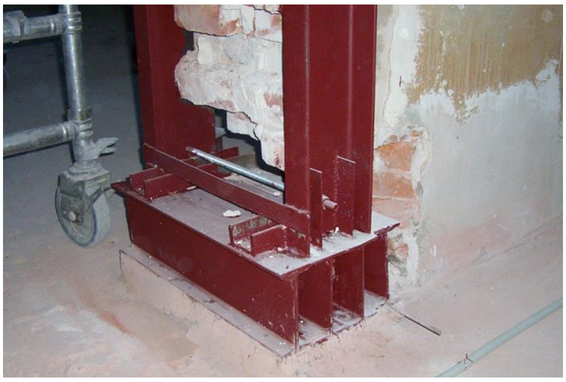
a)

b)



c)

d)



e)

Fig. 17. Making door openings in the inner wall of solid ceramic brick: a) view of the steel frame, b), c), d), e) construction details
(photo: Tomasz Majewski)

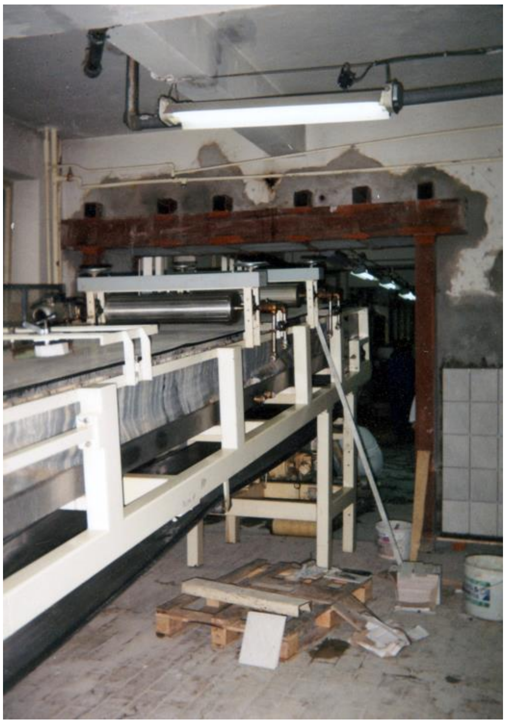


Fig. 18. Widening of the door opening in the inner wall of solid ceramic brick
– view of the steel frame construction
(photo: Maciej Niedostatkiewicz)

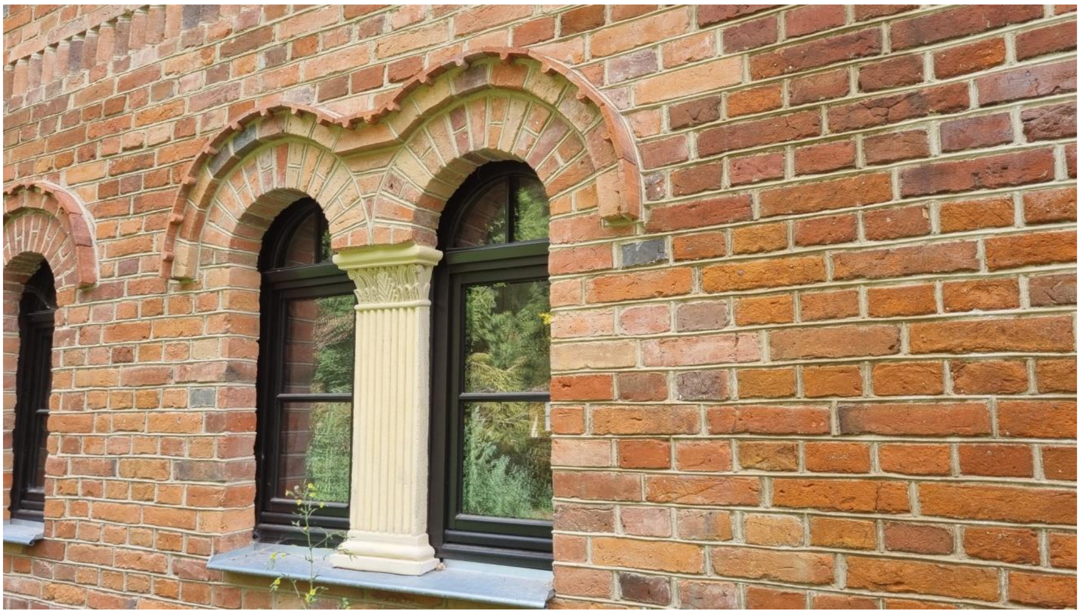


Fig. 19. Revitalization of historic solid ceramic brick wall using contemporary brick
and ceramic tile and limestone details
(photo: Maciej Niedostatkiewicz)

2.10 Transformations in historic agglomerations

As the economic and population growth in historic urban complexes continued, and as people moved toward ever more perfect forms of living, immovable monuments were transformed in accordance with quantitative and qualitative needs and new operating conditions [27], [28]. In many cases, these changes were carried out with disregard for the preservation of the historical values of the buildings, including intensive interference with the structural system during the adaptation of historic buildings for barracks, department stores, warehouses, depots, factories. Very often, the changes carried out in an unstructured manner weakened the structural layout of immovable monuments and promoted the development of destructive processes, and the non-harmonized layering increased the degree of historical and technical degradation of the monuments.

At the same time, the development of urban agglomerations has forced the demolition or partial demolition of historic buildings, including religious buildings, public buildings or historic fortifications.

Taking into account the number of decisions made on the demolition, as well as the complete reconstruction of historic buildings, including decisions resulting from both economic, often as well as socio-political conditions, it is fully justified to maintain and protect surviving immovable monuments, including buildings containing brick masonry elements. One of the forms of protection of such immovable monuments is only their partial demolition, reconstruction with the use of modern elements (Fig. 19) or complete demolition with preservation of the so-called *"witnesses of history,"* according to specific conservation recommendations.

The above-described groups of phenomena contributing to the deterioration of the technical condition or even to the destruction of masonry elements of historic buildings rarely occur separately: most often, the damage to a historic building that has occurred over its lifetime comprises a combination of several of them. Hence, the solution to problems that guarantee the viability of historic buildings must be based on the cooperation of representatives of various scientific and technical specialties, in particular, architectural historians, specialists in historic preservation, structural engineers and specialists in geotechnics, geology, hydrogeologists and land reclamation specialists.

3. CONCLUSIONS

The above-described groups of phenomena contributing to the destruction and deterioration of the technical condition of brick masonry elements of historic buildings rarely occur separately: most often, the damage to a historic building that has occurred over its lifetime consists of a combination of several of them. Hence, the solution of problems that guarantee the survival of historic buildings must be based on the cooperation of representatives of various scientific and technical specialties, in particular, architectural historians, specialists in historic preservation, structural engineers and specialists in geotechnics, geology, hydrogeologists and land reclamation specialists.

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